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Dynamic functional EIT Imaging (df-EIT) – A New Concept for Monitoring Effects on regional Lung Function induced by Respiratory Therapy

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Short title:

Dynamic functional EIT imaging for monitoring regional lung function

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Abstract

EIT can potentially offer useful information for monitoring regional lung function directly at the bedside. However it is not evident which presentation of this information is most suitable for monitoring and how this can be efficiently achieved. Using a conventional EIT movie interpretation is inherently difficult due to the continuously changing image. We propose a novel monitoring method of dynamic functional EIT image generation. This method is a modification of methods used for offline generation of functional EIT images for quantification of different ventilatory conditions. In the current work it has been extended to work online on the last acquired images in such a way that the functional image is continuously updated during data acquisition. The advantage is that for steady state physiological condition the dynamic functional EIT image does not alter thus facilitating visual interpretation. Different dynamic functional EIT images acquired under laboratory and clinical conditions in healthy volunteers and mechanically ventilated patient with the Goe-MF II system will be presented and compared with the information obtained from a sequence of single EIT images.

Keywords

Electrical Impedance Tomography, EIT, ventilation monitoring

1 Introduction

Mechanical ventilation is a standard therapy in patients suffering from acute lung injury (ALI) or adult respiratory distress syndrome (ARDS). However, mechanical ventilation also can induce lung damage (Bernard et al 1994). Furthermore, the development of non-ventilated regions (atelectasis) during mechanical ventilation is a major

problem which can occur within seconds (Neumann at al 1998). Therefore, some ventilatory strategies (e.g. special recruitment manoeuvre) have been proposed to open up atelectasis and keep the lung open (Lachmann et al 1992). Unfortunately, after a recruitment manoeuvre, which opens up the lung, the effect of recruitment can disappear in 15-20 minutes (Villagra et al 2002). In consequence ventilation distribution and regional lung volume are spatially and temporally heterogeneous. Reliable recognition of this heterogeneity may offer a rational basis for respiratory therapy and may enable the optimisation of ventilatory support. Therefore continuous monitoring at the bed-side of regional ventilation, regional lung volume and, thus, alveolar recruitment or de-recruitment is necessary to follow short- and long-term changes in regional lung function induced by respiratory therapy.
Detection of changes in regional ventilation and lung volume in mechanical ventilated patients as guides in the treatment of the patient and setting of the ventilator is not common on the intensive care unit (ICU). The reason for this is that until now measurements are complicated and the benefit may not warrant the efforts (Hinz 2003). X-ray computed tomography delivers information about ventilation distribution and regional lung volume. This method is associated with marked radiation exposure and cannot be used continuously at the bedside. From this, electrical impedance tomography (EIT) may be considered as an imaging technique capable of monitoring of different regional pulmonary parameters directly at the bedside with an excellent temporal resolution without exposure to radiation (Brown 2002, Hinz 2003). However, to our knowledge, this monitoring approach has not been implemented yet in any commercially available EIT device or research instrument. Until now the physiologically relevant information can only be extracted after time-consuming offline evaluation steps. Furthermore, the kind of information which is most suitable for monitoring of ventilation distribution and regional lung volume has not been investigated.
To get information about regional lung ventilation and volume self-adhesive electrodes are placed equidistant around a cylindrical-like object such as a human thorax. Between any two adjacent electrode pairs, a constant electric current is injected into the body under inspection while all other electrodes measure pair wise the resulting voltages at their location (Brown 2003). A modified filtered back-projection algorithm (Barber and Seager 1987) is used to reconstruct individual EIT images from these surface voltages. These individual EIT images represent the spatial distribution of relative impedance changes in one thoracic cross-section compared to a reference physiological state. In general, in healthy volunteers this reference state is collected during normal tidal breathing and in artificially ventilated patients during mechanical ventilation set by the attending physician.
During respiration, from the physiological point of view, this spatial distribution of relative impedance changes represent instantaneous air content changes. It has by itself only limited diagnostic value. However, the derived information allows concise characterization of the lung function. For example, the variation of these impedance changes with time gives information about regional lung ventilation, whereas the mean relative impedance changes correlate with shift in local lung volume compared to the physiological reference state (Hahn et al 1995). In this paper we propose a novel online monitoring approach based on this procedure and exemplary results will be presented in spontaneously breathing healthy volunteers performing specific ventilatory manoeuvres and in mechanically ventilated ICU patients during different ventilatory settings.

2 Methodology

The work being presented here uses the Goe-MF II EIT system (Hahn *et al* 2002), which incorporates a 16 electrode adjacent drive strategy with the ventilation monitoring software running with frame rates of 13, 25 and 44 Hz (Dudykevych *et al* 2002). Series of single EIT images (*EIT Movie*) as well as two types of derived images called dynamic functional EIT images (df-EIT) representing regional lung-ventilation (*lung ventilation* df-EIT images) and shift in lung volume (*shift in lung volume* df-EIT images) will be evaluated for monitoring. The procedure for generation of these images is described below.
Due to the fact that future EIT images cannot be taken into account for proper scaling of the past and current images and that the scaling range is not known a priori, before measurement starts a scaling problem arises in on-line monitoring. This is in contrast to off-line evaluation, where each EIT image can be scaled retrospectively using a series' global minimum and maximum values. Furthermore, the reference choice obviously influences the resulting tomographic data. On the other hand, in general, quantitative interpretation is difficult or impossible when each image is scaled automatically. The scaling problem is approached individually for the three different image types.
EIT Movie. The ventilation monitoring software generates the online conventional EIT movie from consecutive single EIT images as depicted in fig. 1, left. The image orientation in this work is the following: ventral is at the bottom and the right side of the body is on the left of the image. Depending on the state of respirations and the chosen reference the image values range results in either positive or negative value. The scaling problem is approached by starting with initial low range and adjusting the images' scale range by 10 % each time a new image falls below or above current scale. So the free room of maximally 10 % must be taken into account e.g. in the ventilatory steady-state condition.

Lung ventilation df-EIT images. There are two types of derived functional EIT images to be considered for monitoring. The method of off-line generation of functional EIT images was initially introduced by Hahn *et al* in 1995 for quantification of different ventilatory conditions. This approach is now the state-of-the-art in the evaluation of EIT data and has been used in a number of EIT reports (Hahn *et al* 1995, Frerichs *et al* 2001). Briefly, for *lung ventilation* functional EIT image the standard deviation of each local time course from the series of single EIT images, representing a steady state physiological condition, is calculated as a variability measure of the impedance change and the underlying physiological process. Since this is performed on all pixels' time courses, a series of tomograms will be reduced to a single synthetic image. In the current work this method has been extended to work online on the last acquired images using a concept of sliding window, that is the functional image is updated during data acquisition each time a new frame is sampled (fig. 1, right). Obviously, the image values range is always positive, high impedance variation within a thoracic plane physiologically is related to ventilation, low variation is registered in the thorax wall itself. Statistically, physiological processes such as mechanical ventilation with fix ventilator setting or spontaneous breathing can be assumed to be stationary processes as both statistical properties and power density spectrum are time-invariant. Therefore each image can be scaled automatically to provide the maximal colour dynamic range. The scale range will not essentially change over the entire duration of the stationary physiological process as confirmed for the breath-hold manoeuvre and spontaneous breathing in fig. 2(a) for the human volunteer EIT data from fig. 4 described later. The colour bar on the image's right is used to provide the quantitative information which represents the instantaneous physiological variation in the cross-section. Obviously, a stable df-EIT image is obtained when the sliding window length at least matches or exceeds a periodicity of the physiological process to be monitored.

Shift-in-lung-volume df-EIT images. For the *shift in lung volume* df-EIT image generation, the mean value for each time course within a moving window is calculated as a functional parameter instead of variation as in the previous case. The image values range can be either positive or negative as in the case of single EIT images. Therefore unambiguous colour assignment to the distinct shift in lung volume is not possible during automatic scaling, making quantitative interpretation impossible. The problem is approached by these three steps 1) starting with initial low range and adjusting the series' scale range to the current image maximum or minimum each time a new image falls above or below current scale; 2) the image scale is always centred by equalizing the absolute values for maximal negative and positive scale values; 3) the colour bar on the image's right is used to provide the quantitative information about the instantaneous shift in lung volume in the cross-section with respect to the reference state. This dynamic scale adjustment procedure is shown in fig. 2(b) for the human volunteer EIT data from fig. 4 described later. This results in regions with no shift in lung volume always appearing in the same colour regardless of the reference state choice. Furthermore, distinct colours can be associated with the higher and lower lung air content compared to the reference state.

3 Results

Figure 3(a) depicts the global time course of relative impedance change for a healthy spontaneously breathing volunteer. EIT scanning was performed at an acquisition rate of 13 frames/s. The series of individual EIT images, *lung ventilation* and *shift in lung volume* df-EIT images have been generated online. For the time period of about 1.2 seconds, depicted by two vertical solid lines, corresponding to the one half of the breathing cycle from the expiration to the inspiration three series are plotted in a 4x4 arrangement in the figures 3(b), 3(c) and 3(d). Time series of the EIT images are presented in this work going from the upper left to the lower right. The EIT movie runs from dark blue at expiration through green at the mean lung volume to red shades at inspiration. The transition from expiration to inspiration is comparitively smooth since the limits of physiologically induced relative impedance change do not vary in this steady state. In contrast, the *lung ventilation* df-EIT images remain almost unaltered from frame to frame, because the physiological state – ventilation and fluid distribution in the thoracic cross-section – does not change. The nearly homogeneous green shades of the *shift in lung volume* df-EIT images reflect the fact that no change of local lung volume occurs during spontaneous breathing.

Figure 4(a) represents the global time course of relative impedance change for the same volunteer performing an end-expiratory breath-hold manoeuvre followed by spontaneous breathing. As in figure 3, the series of individual EIT images, *lung ventilation* and *shift in lung volume* df-EIT images have been generated online and are shown in figures 4(b), 4(c) and 4(d) for the time period of about 1.2 seconds depicted by two vertical solid lines. The reference for the back-projection reconstruction algorithm is calculated as the mean value from the breath-hold phase. The colours vary synchronously with cardiac-related actions during the first half and changes abruptly as the volunteer starts to breath due to the rescaling process described above. On the other hand *lung ventilation* df-EIT images only emphasize the cardiac-related variations of the relative impedance change during the breath-hold phase (images 1-6), the display alters during transition from breath-hold steady state to the tidal breathing (images 6-9) and "freezes" in this state (images 9-16) emphasizing primarily the pulmonary function. The *shift in lung volume* df-EIT images show

simultaneously the corresponding increase of the mean local lung volume (images 11-16) whereas the first part indicates no significant lung volume changes during breath-hold steady state (images 1-9).
The noticeable effect of the different referencing approaches on the EIT movie is demonstrated in figure 5. The same data as in figure 4 have been reconstructed using an averaged tidal breathing part as a reference. Now, the end-expiratory breath-hold is identified as expiration in the EIT movie and the cardiac-related oscillations have only negligible influence on the EIT movie display. This does not occur in the *lung ventilation* df-EIT image and by comparing the figures 4(c) and 5(c) it becomes obvious that, fortunately, the reference choice has no effect on *lung ventilation* df-EIT image. On the other hand *shift in lung volume* df-EIT image clearly indicates the decreased mean regional lung volume during end-expiratory apnoea, compared to the normal breathing reference state (images 1-8). These changes are cancelled as the volunteer returns to the spontaneous breathing, which is identical to the reference (images 10-16).
Figure 6(a) and 6(b) shows the exemplary changes in the local relative impedance change tracings resulting from an increase in positive end expiratory pressure (PEEP) level from 5 to 15 mbar in one ventral and dorsal lung region for a mechanically ventilated ARDS patient. This series has been referenced on the PEEP level of 5 mbar. In the dorsal region a time-dependent recruitment occurs during PEEP step indicated by an increase of local relative impedance change amplitude after PEEP level has been increased to 15 mbar. In contrast to in the ventral regions after PEEP has increased to 15 mbar a decrease of local relative impedance change amplitude can be observed showing an over-distension.
The corresponding lung-ventilation df-EIT images as displayed online on the running ventilation monitoring software are shown in figures 6(c) und 6(d) and the corresponding *shift in lung volume* df-EIT images are shown in figures 6(e) und 6(f) respectively for two sliding windows depicted in 6(a) and (b). Both, the *lung ventilation* df-EIT images and the local time courses clearly show the ventilation redistribution from ventral to dorsal lung regions resulting from the PEEP step indicating dorsal alveolar recruitment. The *shift in lung volume* df-EIT images (fig. 6(e) and 6(f)) indicate the corresponding increase in mean regional lung volume, compared to the mechanical respirator PEEP level of 5 mbar.

4 Discussion and Conclusion

The results demonstrate that EIT movie is not the most convenient approach for monitoring of regional lung ventilation and shift in regional lung volume in the clinical settings as unambiguous colour scale assignment is not possible online. This is due to the facts that 1) the colour varies periodically through the whole dynamic range even in physiological or clinical steady state conditions (e.g. during normal tidal breathing in fig. 3(b)); 2) during transition from one state to another physiological information is superimposed by artefacts dependent on the selected reference state and the induced rescaling process as depicted in fig. 4(b) and 5(b). In contrast, df-EIT images produce only marginal visible changes under steady-state physiological condition (fig. 3(c), 4(c), 5(c)) facilitating visual interpretation. Marked rapid changes will only occur in an unsteady-state transition phase as e.g. in transition from respiratory apnoea to tidal breathing or as a result of changing mechanical ventilator settings (fig. 6(c), (d) and 6(e), (f)). Furthermore distinct colour shades can be associated with particular physiological conditions. By using the well known pseudo-colour shading (fig. 1), in the *lung ventilation* df-EIT images, yellow and red shades are related to ventilation whereas blue are registered in the regions with low physiological variation as in the thorax wall. In the *shift in lung volume* df-EIT images, the regions with no regional mean lung volume change are presented by green shades, yellow and red are related to regions with increased volume values whereas blue corresponds to the regions with decreased lung volume compared to the reference physiological state.
The technique of dynamic functional EIT imaging presented here will expand the capability of EIT for monitoring and imaging. From the technical and operational point of view, overall measurement plausibility checks will be possible for the first time during a data collection. From the medical point of view, the regional lung ventilation and shift in lung volume can be continuously monitored by EIT similarly to conventional heart rate or blood pressure monitoring. Df-EIT offers an immediate visual impression of effects of clinical or experimental interventions. In particular, dynamical functional EIT seems to be a helpful tool to detect alveolar recruitment during mechanical ventilation and to set the respirator parameters for each individual patient optimally.

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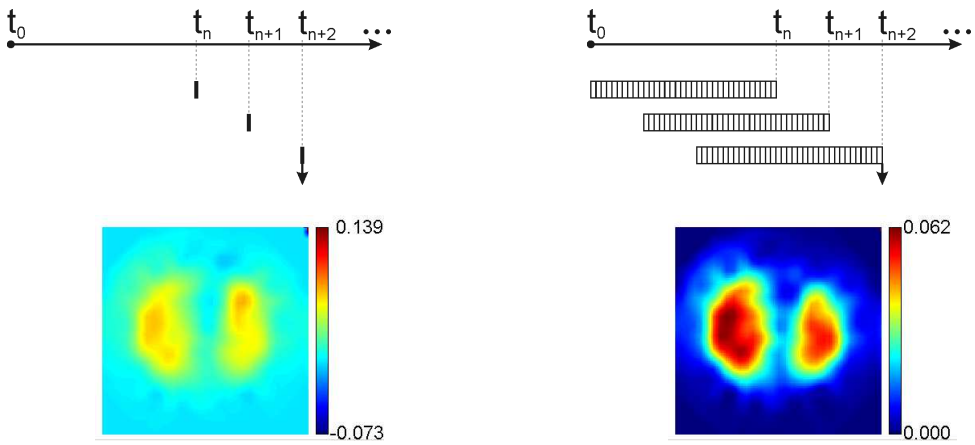
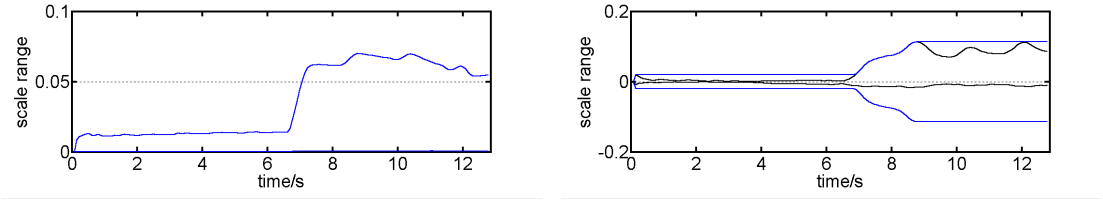


Fig. 1. Comparison of generation procedure of series of the individual EIT images (left) and df-EIT images (right) and the images of a healthy spontaneously breathing volunteer.

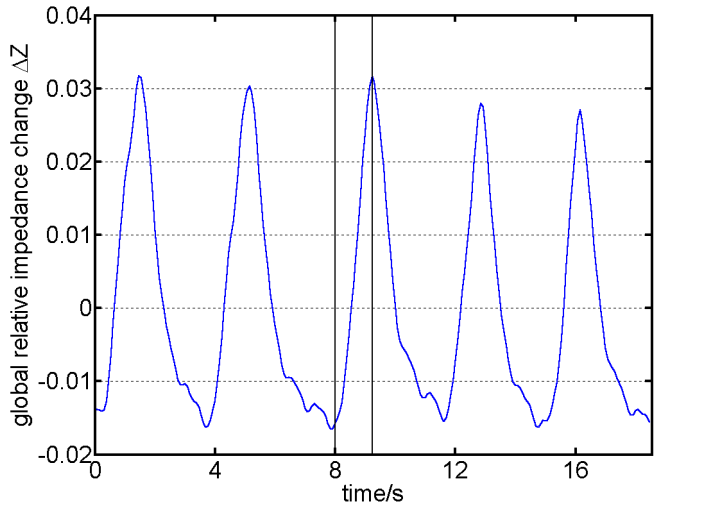


(a) (b)

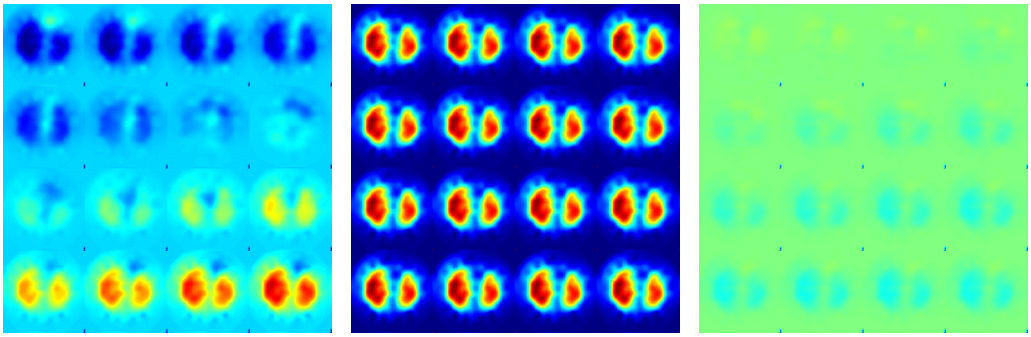
Fig. 2. Dynamic scale adjustment procedure for *lung ventilation* (a) and *shift in lung volume* (b) df-EIT images for a healthy spontaneous breathing volunteer performing a breath-hold manoeuvre during six seconds followed by normal breathing. See for details fig. 4.

a) For *lung ventilation* (b) df-EIT images scale range is adjusted automatically

b) Black lines represent the maximum and minimum of each single *shift in lung volume* df-EIT images whereas blue lines depict scale range calculated according to the procedure described in the text.



(a)



(b) (c) (d)

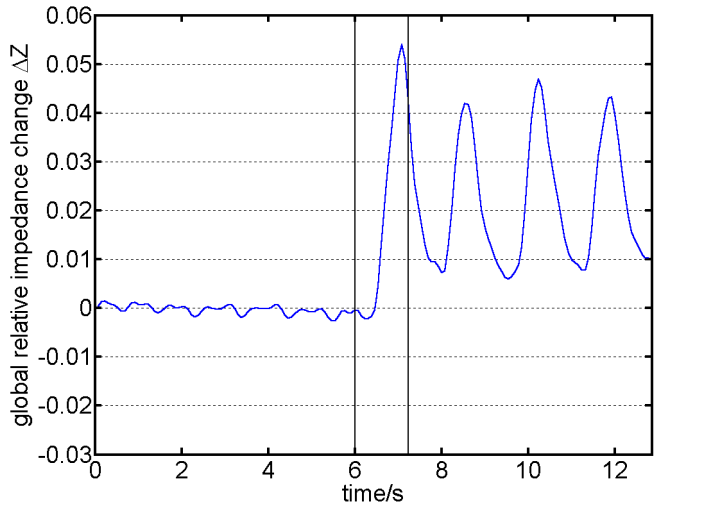
Fig. 3.

a) Global time course of relative impedance change in a healthy volunteer performing 5 normal breaths. Note that during inspiration relative impedance change increases while during expiration relative impedance change decreases

b) Series of individual EIT images during one inspiration between the solid vertical lines of 3(a). Time series of the EIT images are presented going from the upper left to the lower right. Regional air content increases during inspiration as indicated by colour changes from dark blue to red

c) Series of *lung ventilation* df-EIT images indicate that the ventilation distribution does not change during normal tidal breathing

d) Series of *shift in lung volume* df-EIT images indicate that distribution of mean regional lung volume does not change



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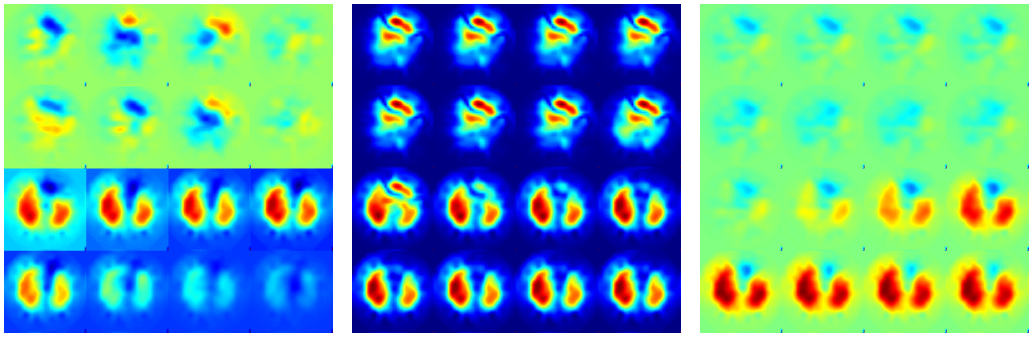


(b) (c) (d)

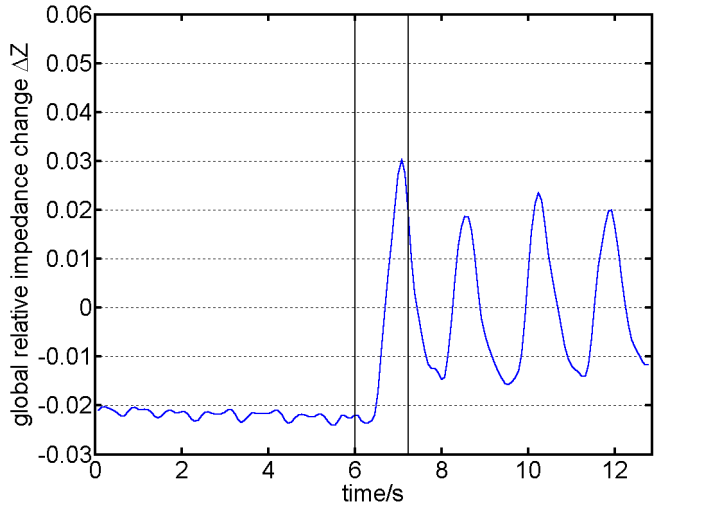
Fig. 4.

a) Global time course of relative impedance change in a healthy spontaneous breathing volunteer during initial breath-hold during six seconds followed by normal breathing. The measurement was referenced on the initial breath-hold manoeuvre. During the breath-hold cardiac related impedance change are observed.

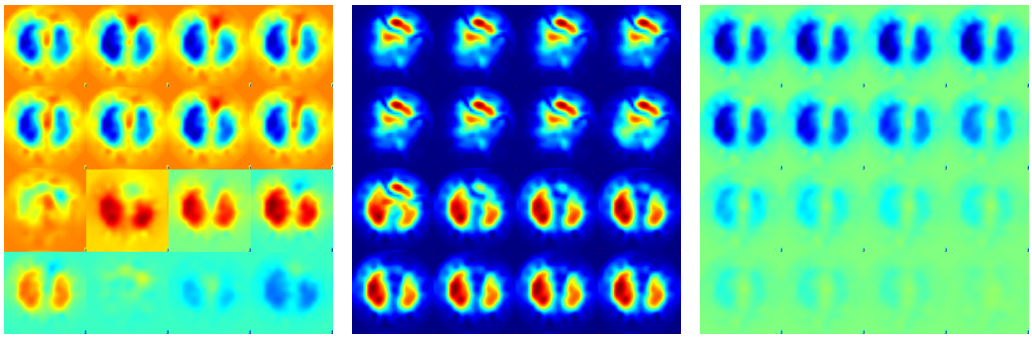
b) Series of individual EIT images during transition from breath-hold to end-inspiration and a part of expiration (period: solid vertical lines of 4(a)). Time series of the EIT images are also going from the upper left to the lower right. The colours vary synchronously with cardiac-related actions during the first half (images 1-8) and changes abruptly as the volunteer starts to breath due to rescaling process as described in the text.

c) Series of *lung ventilation* df-EIT images showing that cardiac action influencing impedance change and that the ventilation distribution does not change during normal tidal breathing

d) Series of *shift in lung volume* df-EIT images. Note the increase of mean regional lung volume.



(a)



(b) (c)

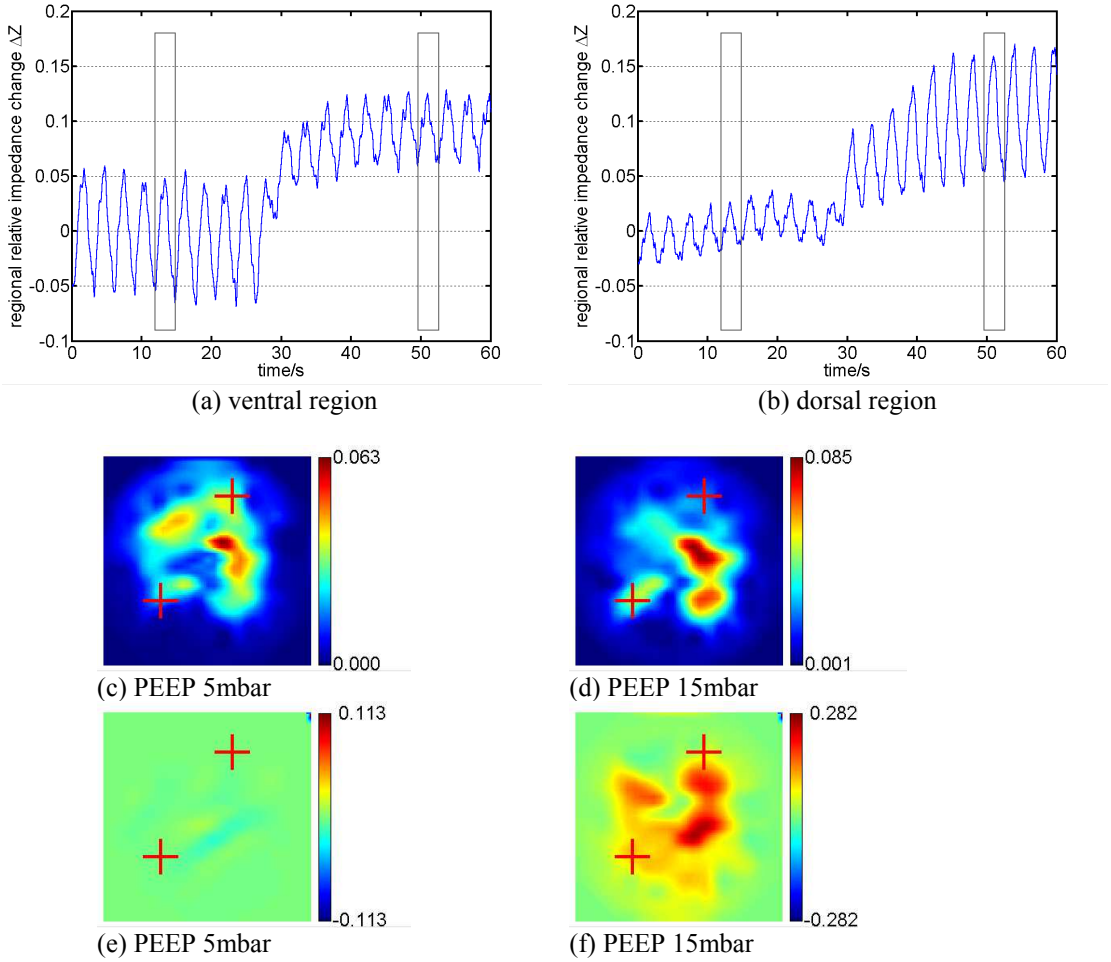
Fig. 5.

a) Global time course of relative impedance change in a healthy spontaneous breathing volunteer during initial breath-hold during six seconds followed by normal breathing. The measurement was referenced on the normal breathing. During the breath-hold cardiac related impedance change are also observed as in fig. 4.

b) Series of individual EIT images during transition from breath-hold to end-inspiration and a part of expiration (period: solid vertical lines of 4(a)). Time series of the EIT images also go from the upper left to the lower right. The initial breath-hold is now identified as end-expiration due to the changed reference in contrast to fig. 4. (images 1-8) and changes abruptly as the volunteer starts to breath due to rescaling process as described in the text.

c) Series of *lung ventilation* df-EIT images showing that cardiac action influencing impedance change and that the ventilation distribution does not change during normal tidal breathing. Note that the changed reference does not influence the images as in fig. 4(c)

d) Series of *shift in lung volume* df-EIT images. Note the decreased mean regional lung volume during end-expiratory breath-hold referred to the normal breathing reference state.



(a) ventral region

(b) dorsal region

(c) PEEP 5mbar

(d) PEEP 15mbar

(e) PEEP 5mbar

(f) PEEP 15mbar

Fig. 6.
(a), (b) Local time courses of relative impedance change in a mechanically ventilated ARDS patient from a ventral lung region (a) and a dorsal lung region (b), respectively during PEEP step manoeuvre from 5 to 15 mbar at 28 s. In the dorsal region a time-dependent recruitment occurs during PEEP step indicated by an increase of local relative impedance change amplitude after PEEP level has been increased to 15 mbar. In contrast to in the ventral regions after PEEP has increased to 15 mbar a decrease of local relative impedance change amplitude can be observed showing an over-distension.

(c), (d) *Lung ventilation* df-EIT images as displayed on the ventilation monitoring software for two sliding windows at PEEP 5 mbar (left window in fig. 6(a) and (b)) and PEEP 15 mbar (right window in fig. 6(a) and (b)), representing instantaneous ventilation distribution for two different positive end expiratory pressure (PEEP) levels in a mechanically ventilated ARDS patient.

(e), (f) *Shift in lung volume* df-EIT images as in fig. 6(c) and (d), representing changes in mean local lung volume induced by two different positive end expiratory pressure (PEEP) levels.

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